MODULATING PERIPERSONAL AND EXTRAPERSONAL REACH SPACE:

A DEVELOPMENTAL PERSPECTIVE

A Dissertation

by

PRISCILA MARTINS CAÇOLA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2011

Major Subject: Kinesiology

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Approved by:

Chair of Committee,	Carl Gabbard
Committee Members,	John Buchanan
	David Wright
	Teresa Wilcox
Head of Department,	Richard Kreider

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ABSTRACT

Modulating Peripersonal and Extrapersonal Reach Space:

A Developmental Perspective.

(August 2011)

Priscila Martins Caçola, B.S., Federal University of Parana;

M.S., Federal University of Parana

Chair of Advisory Committee: Dr. Carl P. Gabbard

The primary intent of this study was to gain insight into the developmental nature of spatial perception and representation. More specifically, the work presented here examined 1) the age-related ability to modulate peri- and extrapersonal space via hand and tool use, 2) the adjustment period associated with extending and retracting spaces, and 3) the effect of tool length on modulation of space. Seventy children representing age groups 7-, 9-, 11 years and adults were presented with two experiments using an estimation of reach paradigm involving hand and tool conditions and a switch-block of the opposite condition. Experiment 1 tested Hand and Tool (20cm length) estimation and found a significant effect for Age, Space, and an Age x Space interaction (*ps* <.05). Both children and adults were less accurate in extrapersonal space, indicating an overestimation bias. Interestingly, the adjustment period during the switch-block condition was immediate and similar across age. Experiment 2 was similar to Experiment 1 with the exception of using a 40cm length tool. Results of 55 participants also revealed a difference in estimation responses between Age groups (*p* <.05); 7- and

9-year-olds were similar and less accurate than adults, and 11-year-olds were not different from any other age group. There was also a difference in Space (p <.05), revealing that participants underestimated their reaching abilities with higher accuracy in extrapersonal space. Interestingly, whereas participants overall overestimated with the 20cm tool, they tended to underestimate while using the 40cm tool. This finding suggests that participants were less confident when presented with a longer tool, even though the adjustment period with both tool lengths was similar. Considered together, these results hint that: (1) children as young as 6 years of age are capable of re-scaling peripersonal space via tool use in the context of estimation reach, (2) the adjustment period associated with extending and retracting spaces is immediate rather than gradual, and (3) tool length may influence confidence of participants, shifting the general direction of error from overestimation with a 20cm tool to underestimation with a 40cm tool.

DEDICATION

To my friend Eliana, for her infinite patience listening to all the struggles that have accompanied my Ph.D. journey.

ACKNOWLEDGEMENTS

My sincere gratitude goes primarily to my mentor, Dr. Carl Gabbard. Throughout the last few years, he has shared his knowledge, experience, and, above all, friendship that I will cherish for many years to come. I was very lucky to be advised by him.

I am thankful for meeting Dr. Patricia Goodson, who mentored me in many diverse matters of academia and taught me that the talents I did not initially possess could be learned over time with the right techniques. I only truly believed in myself after I met her.

I would like to thank all the members of my committee: Dr. John Buchanan, for having critical questions that always made me think harder; Dr. David Wright, for his consistent motivating attitude; and Dr. Teresa Wilcox, for her support and smiles in moments of difficulty. I also would like to thank Dr. Charles Shea, for all the statistical advice he provided in the last 4 years.

I could not have finished (or even started) my Ph.D. without the financial support I received from the PEAP Program and the HLKN Department, and their trust I was worthy of an assistantship. In addition, I am thankful (and humbled) for having being entrusted scholarship awards from the American Association of University Women (2008-2009), the P.E.O. Sisterhood (2009-2011), and the Margaret McNamara Fund (2010-2011).

It is impossible to pursue any research alone. I would like to thank my lab co-workers, Tatiana Bobbio, Alberto Cordova, and Brittney Oliver, the wonderful student workers, Mary Kunst and Jessica Gengo, and all undergraduate research assistants. Their participation was fundamental in data collection, organization, and analysis, and their help is immensely appreciated.

The data collection stages of this dissertation would not have been possible if it were not for the kindness of camp directors (Ms. Martha Muckleroy and Mr. Mike Hanik), who graciously let me disturb their work so I could test children during their camp hours. Also, the generosity of all the busy parents who brought their children to the lab will not be forgotten.

I am appreciative of all the children who graciously participated in the data collection process. Whether they participated in summer camps or came with their parents, they were always willing to do their best. I hope that the fun I had was reciprocal.

Above all, a higher power has supported me throughout different moments of this trajectory by allowing me to meet a handful of important people. Their friendship and care showed me the grace of God in different times of this journey, and for that I will always be thankful.

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CHAPTER I

INTRODUCTION

Effective reaching requires an integrated neural representation of the body and of the space surrounding the body; that is, *peripersonal* and *extrapersonal* space. Peripersonal (near) space is behaviorally defined as the space within the hand-reaching distance, whereas extrapersonal (far) space represents the area outside the hand-reaching distance. The coding of space as near and far is not only determined by the hand-reaching distance, but it is also dependent on how the brain represents the extension of the body space (Berti & Frassinetti, 2000).

One of the lines of research associated with the general topic of space is tool use. Although the length of our effectors (arms and hands) limits our action space, we can use many different tools (e.g., sport implements: real and virtual [Wii]) to extend our physical body structure and, consequently, our action space. In recent years, numerous studies have focused on this aspect of spatial recognition and its link to subsequent motor planning and action. Underscoring the intent of the present study is the observation that the developmental course and distinction between peripersonal space and extrapersonal space remains largely unexplored (Bremner, Holmes, & Spence, 2008).

Part of the motivation for this project derived from recent work in our laboratory showing that there are differences between children and young adults in estimates of

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This dissertation follows the style of *Journal of Motor Behavior*.

reach (Gabbard, Cordova, & Ammar 2007; Gabbard, Cordova, & Lee, 2009b). More precisely, when viewing reaching space as peripersonal (within grasp) and extrapersonal (beyond reach), children display a distinct 'body-scaling' problem in extrapersonal space; a problem not shown in adults. While we found no studies exploring children's modulation of space by tool use, a large body of literature suggests that tool use extends peripersonal space in adults. We argue that if children have the same ability to modulate space with a tool as adults, it is possible that their body-scaling "problem" is simply the result of developmental issues in space perception.

Therefore, the primary goal of this study was to gain insight into the developmental nature of spatial perception and representation. To this end, two experiments addressed the following: 1) the age-related ability to modulate peri- and extrapersonal space via hand and tool use, 2) the adjustment period associated with extending and retracting spaces, and 3) the effect of tool length on modulation of space. Our assumption was that children would show less accuracy than the adult group. We also expected to find no differences between hand and tool conditions in each age group. This prediction was based on evidence suggesting that tool use result in an expansion of the body schema and peripersonal space.

The following is a brief background of the relevant areas of research associated with this dissertation, namely: Peripersonal and extrapersonal space, tool use, and a developmental perspective, respectively.

Peripersonal and Extrapersonal Space

Human beings represent space surrounding them while performing everyday activities, and a successful completion of those activities depend on an accurate space representation. For example, situations such as parking a car, deciding how far we need to reach to grab a cup of coffee, or whether we need a broom to reach for something that fell under the bed are examples of our abilities to accurately (most of the times) represent space. Generally speaking, the human body is the focus of certain spatial representations. Contemporary research suggests that spatial representation is not uniform, but multiple and flexible. To simplify, there appears to be at least three spatial representations originating from the body (see Rizzolatti, Fadiga, & Fogassi, 1997): the body space (de Vignemont, 2010), the space far from the body, i.e. not reachable by a simple movement of the arm, named *extrapersonal space*, and the space immediately surrounding the body, known as *peripersonal space.*

Closely associated with the notion of space representation are the findings that there are specialized visual neurons coded for the detection of near space (Iriki, Tanaka, & Iwamura, 1996; Làdavas, 2002). In other words, evidence shows that the brain codes space in terms of reachability. In monkeys, bimodal neurons, coders for peri- and extrapersonal space, have been described in inferior parietal areas and the premotor cortex (Duhamel, Colby, & Goldberg, 1998; Fogassi et al., 1996; Graziano & Cooke, 2006; Graziano & Gross, 1998). These neurons have the characteristics to be activated by visual as well as somatosensory stimulations, with a higher activity for closer (peripersonal) than farther visual stimuli. In humans, a functionally homologous coding of peripersonal space is largely supported by behavioral studies, showing stronger visual–tactile interaction in near than far space in brain damaged patients (Brozzoli, Demattè, Pavani, Frassinetti, & Farnè, 2006; Farnè, Demattè & Làdavas, 2003; Làdavas & Farnè, 2004) and healthy individuals (Bremmer, Schlack, Duhamel, Graf, & Fink, 2001; Pavani & Castiello, 2004; Spence, Pavani, & Driver, 2000; Spence, Pavani, Maravita, & Holmes, 2004).

The representation of space near the body, termed 'peripersonal space' (Rizzolatti, Fadiga, & Fogassi, 1997), appears to rely on multisensory processing. Bimodal neurons (previously described) put together information across parieto-frontal and subcortical structures, coding tactile events on a body-part (e.g., the hand) and visual events near that body-part. The information obtained gives rise to body-centered representations of peripersonal space (Rizzolatti et al., 1981, 1997; see for review Rizzolatti, Fogassi, & Gallese, 2002).

Adding to the notion of multiple representations of peripersonal space, Brozzoli and colleagues (2010) found that a continuous updating of that space occurs during action execution. Spatial representation is viewed as multiple and flexible, because it can be re-scaled as we act on the world. This re-scaling of space varies with different characteristics of a given motor act – for example, voluntarily acting on objects triggers specific re-scaling of multisensory perception as a function of action requirements; and it is possibly the result of either motor complexity alone, or its coupling with spatial information about the target object.

Therefore, peripersonal space representations have basically a motor function: spatial locations of multisensory stimuli are encoded in relationship to body parts to generate appropriate motor responses (goal-directed, defensive or avoidance movements) (Graziano & Cooke, 2006; Ladavas & Farnè, 2004; Legrand, Brozzoli, Rossetti, & Farné, 2007; Rizzolatti et al., 1998). Normally, peripersonal space (such action space) is delimited by the physical length of body effectors (limbs). Tools can be used as physical extensions of those body effectors, enabling one to reach and interact with distant objects (see subsequent section on tool use).

Tool Use

One of the lines of research associated with space perception and representation is tool use. In the ecological view, a tool is an object attached to the body in such a way as to extend the organism's capacity for perceiving and acting. For example, although the length of our effectors (arms and hands) limits our action space, we can use many different tools (e.g., sport implements: real [tennis racquet] and virtual [Wii]) to extend our physical body structure and, consequently, our action space. Tool use represents a window into the plasticity of body and spatial representation.

A tool modifies, at least temporally, the body schema, which is considered a functional element for perceiving one's own body in environmental space. Altered action capabilities with the tool are accurately represented in the body schema, resulting in the modification of an individual's representation of space (Higuchi, Imanaka, & Patla, 2006).

The modification of the body schema due to tool use is related to the notion of embodiment. Embodiment refers to the representations of the external environment in relation to the perceiver's body (including their individual limbs). They are required if one is to act upon the environment. A typical example of embodying is a blind person's stick. When probing the ground, an unpracticed person feels the impact of the stick at the hand and perceives the ground through it. As the person gets accustomed to using it, the person perceives the ground directly, and thus the stick is no longer sensed for itself. If an inorganic tool, such as a blind person's stick, support information gathering, the tool is regarded as a component of the perceptual system. That is, tool use is regarded as an extension of the perception–action systems (Hirose, 2002).

Considerable attention has been devoted to behaviors in which tools are used to perform actions in extrapersonal space by extending the effector (reach). Evidence suggests that these behaviors result in an expansion of the body schema and peripersonal space. Furthermore, research findings indicate that tool use (temporary extension of the limb) can modulate the borders between peri- and extrapersonal space (Berti & Frassinetti, 2000; Gamberini & Seraglia, & Priftis, 2008; Holmes, Calvert & Spence, 2004; Longo & Lourenco, 2006; Maravita & Iriki, 2004; Neppi-Modona et al., 2007). Complementing this modulation is the 're-scaling' of extrapersonal to peripersonal space. For example, a tool can increase the spatial extent of the representation of peripersonal (hand) visual space to incorporate the tool (Làdavas & Farnè, 2004).

The brain should represent objects situated in peripersonal space differently from those in extrapersonal space (Coello et al., 2008). For example, Iriki et al. (1996) found neurons in the intraparietal sulcus that fired when a raisin was presented within a monkeys' arm's reach but not beyond. The monkeys were then taught to reach with a rake, which extended their reach. The so-called ‘reachability neurons’ adapted to this change and responded to raisins that were presented further away, but within reach with the rake. This research suggests that there exists visual neurons that code for what is within reach and that these neurons adapt to changes in reachability, resulting from tool use.

Peripersonal space representation is particularly important, because only within its limits can the body directly interact with the external world (Magosso et al., 2010). This general finding of re-scaling of far space as near space by using a tool has also been demonstrated with healthy adults and with patients showing spatial neglect (e.g., Berti & Frassinetti, 2000; Cardinali et al., 2009; Farnè & Làdavas, 2000; Làdavas, 2002; Neppi-Mòdona et al., 2007; Witt, Proffitt, & Epstein, 2005). Berti and Frassinetti (2000) examined the effect of tool-use in a brain-damaged patient, whose neglect selectively affected her peripersonal space. When requested to show the midpoint of a drawn line, the patient put her mark further towards the right from the objective midpoint, as typically observed in neglect. However, when lines were presented in the extrapersonal space, the patient’s bisections using a laser pointer were flawless. By contrast, when a long stick was used for the same far-line bisection, the patient showed a rightward bias again. The authors concluded that when the stick made far space reachable, it was automatically coded by a neural network selective for near space whereby neglect was selectively present in the patient.

Similar integrative properties of spatial representation in humans have been described in neuropsychological studies conducted on brain damaged patients with cross-modal extinction. In these patients, the perception of contralesional tactile stimuli was affected by concurrent ipsilesional visual or auditory stimuli, and this effect is much stronger when visual or auditory stimuli are presented close to the patient's body, in the extrapersonal space (Farnè & Làdavas, 2000). The near-far modulation of cross-modal extinction has been considered the behavioral hallmark of multisensory integrative systems that code space in humans (see Làdavas & Farnè, 2004; Làdavas & Serino, 2008 for reviews).

In addition, it appears that the re-scaling of space does not depend only on tools that "physically" extend the space. Virtual tools can modulate space as well. For example, a study by Bassolino et al. (2010) investigated the extension of near space via the use of a computer mouse. This is a special tool, because the space where it is used and the space where it exerts an effect are not physically connected. Three conditions were investigated: (1) a baseline condition, in which no use of the mouse was required, (2) a condition in which the mouse was actively used, and (3) a condition in which the mouse was passively held by the subject. Two main general findings were obtained. First, findings showed that a long-term, everyday experience of mouse-use resulted in a durable extension of the boundaries for the space around the hand to the space around the computer screen - such extended representation was automatically evoked not only when subjects actively use the mouse, but also when they passively hold it. Second, the plastic effect due to long term mouse-use experience was selective for the hand with which the mouse is operated.

These results are new for several reasons. First, they show that an extension of peripersonal space can be achieved not only by using a solid medium that physically reaches the far space, but also with a tool that establishes a virtual functional connection between the space of the agency and that of the action goal. Most previous studies in the field have investigated the effects of tools that “only” physically link peripersonal and extrapersonal space, such as rakes used to reach distant food (Iriki et al., 1996) or objects in distant space (Farnè & Làdavas, 2000), long sticks used to press a distant button (Holmes et al., 2004), to reach distant targets (Maravita et al., 2001) or to bisect a line placed in a distant position (Berti & Frassinetti, 2000; Neppi-Mòdona et al., 2007), or white sticks used by blind people to detect obstacles (Serino et al., 2007).

Modulation of space can be also studied from the perspective of the time that it takes for the representation to be re-scaled. Such modulation of space is seen as gradual by Longo and Lourenco (2006), whom suggested that the representation of near (peripersonal) space is “less rigid, extending with tool use and gradually transitioning into far space. On the other side, Gamberini et al. (2008) contradicted this view, suggesting that the transition between spaces is rather abrupt. Higuchi et al. (2006) emphasized the ability of the CNS to adapt to altered action capabilities is very quick, for well-learned motor actions.

In summary, research findings indicate that with tool use, there are neural adaptations that re-scale far space as near space. Evidence also shows that the brain codes space in terms of reachability. For both physical and virtual use of tools, there is modulation of the borders between peri- and extrapersonal space. This modulation can be gradual (Longo & Lourenco, 2006) or abrupt (Gamberini et al., 2008).

Developmental Perspective

Underscoring the intent of the present study is the observation that the developmental course and distinction between peripersonal space and extrapersonal space remains largely unexplored (Bremner, Holmes, & Spence, 2008), and previous work indicating that there are differences between children and young adults in estimates of reachability regarding space (Gabbard et al., 2007; Gabbard, Caçola, & Cordova, 2009a). More precisely, when viewing reaching space as peripersonal and extrapersonal, children displayed a distinct 'scaling' problem in extrapersonal space; a problem not shown in adults. In addition, children revealed a greater overestimation bias.

Although the developmental research is sparse, there are indications that young infants have some form of spatial representation in peripersonal space when planning and executing reach movements. Infants can perceive that near space can be extended to accommodate reachability. That is, the perception that in order to reach something that is initially out of reach, an adjustment must be made. For example, McKenzie et al. (1993) observed that by 8 months of age, infants perceived that leaning forward extends the range of contact beyond that of reaching alone. And of particular interest to us, by 12 months they perceived that they could use a tool (in that case, a rod) to extend peripersonal space.

As Bremner and colleagues (2008) point out however, the process of perceiving a tool as a possibility for extending space is far from trivial. During the early developing years there is a need for constant postural re-mapping due not only to changes in body position, but changes in body size (relative sizes and shapes of the limb, body, and head), that are likely to be associated with changes in spatial perception and action planning. Yet to our knowledge, there are no studies to date on the development of space perception and representation across childhood.

The development of space perception and representation in childhood has significant implications from an applied perspective. Those representations must be constantly updated with the changes in the body size over the years, and with the different types of tools that children use. One example would be the learning process of using a tennis racquet successfully. We can speculate that children take longer and have more difficulties when incorporating the racquet to their body schema, but nothing has been studied to this day, to the best of our knowledge. We believe that the study of tool use will give us a window into the plasticity of body representation and space coding in childhood and adolescence.

Purpose of the Study

The primary goal of this study was to gain insight into the developmental nature of spatial perception and representation in reference to children's modulation of peri- and extrapersonal space with the hand and tool. To this end, we conducted two experiments that answered the following research questions:

Is there an age-related ability in modulation of peri- and extrapersonal space?

Is there an adjustment period associated with extending and retracting spaces? If *so, how long is this period?*

Is the ability to modulate space and the adjustment period related to the length of the tool used?

Experiments 1 and 2 compared estimation of reach responses between hand and tool, with specific attention to the adjustment between conditions across trials. Although our attention focused on the development of the ability to modulate space, we were also interested in the influence of tool length on space perception and the adjustment period associated with extending space with a tool or retracting to the hand. Our assumption was that children would show less accuracy than the adult group. We also expected to find no differences between hand and tool conditions in each age group. This prediction was based on evidence suggesting that tool use result in an expansion of the body schema and peripersonal space.

CHAPTER II

EXPERIMENT 1

With Experiment 1, we examined the age-related ability to modulate peripersonal and extrapersonal space via hand and tool use. In addition to performance outcome over trials, we determined the adjustment period associated with extending and retracting spaces. These two processes were explored using a paradigm for comparison of estimation of reach responses between effector (hand) and tool (antenna), with specific attention to the adjustment between conditions across trials. This tactic involved the comparison of children and adults' tool use (compared to use of their own effector) in estimating reachability via motor imagery in peripersonal and extrapersonal space.

Furthermore, the aim of this experiment was to gain a better understanding of the developmental nature of spatial recognition and action representation in space. One of the initial steps in planning reaching movements is to derive a perceptual estimate of the object's distance and location relative to the body. Obviously, perceptual estimates change when using a tool. In order to plan reach movements, one runs a simulation of the motor action, also known as action representation. Action representation is the ability to mentally represent the intended action. Researchers have presented a rather convincing case that motor imagery provides a window into the process of action representation, which is critical in effective action planning (Caeyenberghs, Tsoupas, Wilson, & Smits-Engelsman, 2009; Gabbard, 2009; Jeannerod, 2001; Munzert, Lorey, & Zentgraf, 2009; Wolpert & Flanagan, 2001).

Motor imagery, also known as kinesthetic imagery, is an active cognitive process during which the representation of a specific action is internally reproduced in working memory without any overt motor output (Decety & Grèzes, 1999). The use of imagery is a widely used experimental paradigm for the study of cognitive aspects of action planning and control. One of its merits is the fact that there is a close association between real and imagined movements (e.g., Glover, Dixon, Castiello, & Rushworth, 2005; Heremans, Helsen, & Feys, 2008; Michelon, Vettel, & Zacks, 2006; Nikulin, Hohlefeld, Jacobs, & Curio, 2008; Sharma, Jones, Carpenter, & Baron, 2008; Young, Pratt, & Chau, 2009). For example, like real movements, simulated actions are sensitive to task complexity (Solodkin, Hlustik, Chen, & Small, 2004; Stevens, 2005) and perceived postural constraints (Bakker et al., 2008; Gabbard et al., 2009b).

The form of motor imagery used here, was *estimating (perceived) reachability*, which involves the cognitive judgment of whether an object is within or out of grasp. This form of imagery requires that participants kinesthetically 'feel' themselves executing the movement ("feel your arm extending…"); therefore being especially sensitive to the biomechanical constraints of the task. This task involves the first-person mental simulation of action that 'focuses' on the effector (reaching unit). Arguably, estimation of whether an object is reachable or not via the use of mental (motor) imagery from a specific body position, constitutes an important aspect in effective action representation and motor planning. That is, an individual must be able to perceive critical reach distances beyond which a particular reach action is no longer afforded and to which a transition to another reach mode must occur. Coello and Delevoye-Turrell

(2007) suggested that this form of simulated action provides the self with a 'pre-reflective' experience of body capabilities.

Regarding the development of motor imagery, recent research using both subjective and objective measures of motor imagery indicated that children as young as 5 years of age have the ability to also imagine movements (Funk et al., 2005), and this ability appears to be still emerging at 7 years of age (Molina, Tijus, & Jouen, 2008; Frick et al., 2009). Although this research is limited, there are indications that, similar to adults, children exhibit the tendency to overestimate their reaching abilities (e.g., Gabbard et al., 2007; Rochat, 1995; Schwebel & Plumert, 1999). More precisely, children have greater problems with extrapersonal when compared to peripersonal space. Therefore, our assumption was that children would show less accuracy than the adult group. We also expected to find no differences between hand and tool conditions in each age group. This prediction is based on evidence suggesting that tool use result in an expansion of the body schema and peripersonal space.

Method

Participants

Experiment 1 involved 70 participants representing four age groups: 6 -7 years (*n* = 11), 8-9 years (*n* = 12), 10-12 years (*n* = 17) and a group of adults, 19-23 years (*n* = 17). The mean ages were 6.86, 8.35, 11.10, and 21.53 years respectively. All participants were screened using a questionnaire (filled out by the parent in the children groups) to ensure normal vision and that none have a history of past or present sensorimotor impairment. For the purposes of this study, only participants identified as strong right-handers via manual performance rather than questionnaire were selected. That is, those for whom all items scored in that lateral direction using the Lateral Preference Inventory (Coren, 1993) were included in the investigation.

The experimental protocol and consent form were approved by the Texas A&M Institutional Review Board (IRB) for the ethical treatment of human subjects. The participants were informed of the experimental procedures and voluntarily signed a consent form before participating in this study (children provided verbal consent after parents signed the consent form).

Apparatus

A general illustration of the testing apparatus is shown in Figure 1 and has been reported elsewhere with adults (Gabbard et al., 2009b) and children (Gabbard et al., 2007, 2009a). Actual maximum reach (used as the comparison) and simulated reach responses were collected via an overhead projection system linked to a PC programmed with *Visual Basic*. Visual images were systematically projected onto a table surface at midline (90^{o}).

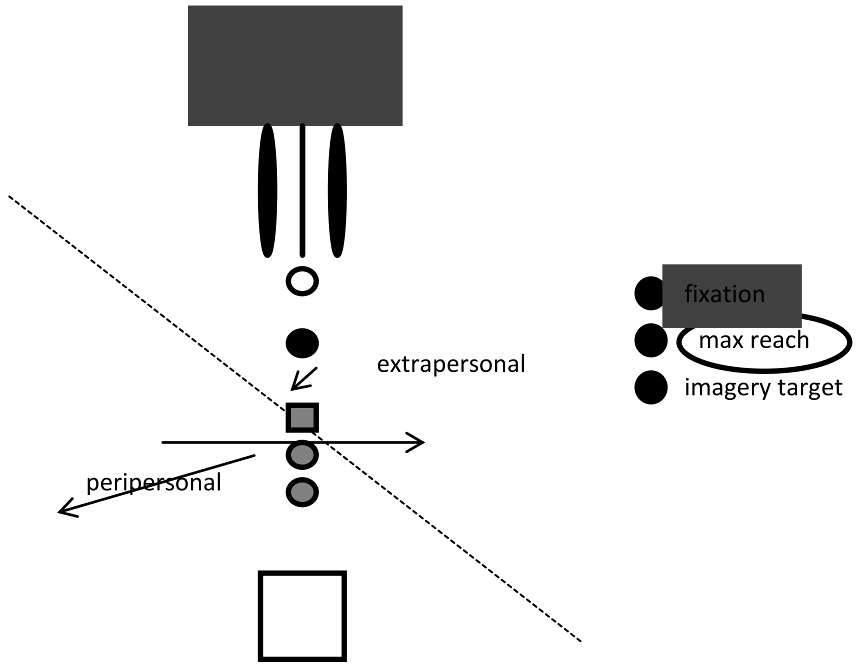

Figure 1. General experimental set-up.

The table was constructed on a sliding bracket frame, allowing it be moved back and forward for adjustment to the participant. Participants sat in an adjustable ergonomics chair fixed to the floor, aligned with the midline of the table and projected image midline. Seatpan height (surface was metal and nondepressive) was set to 105% of participant's popliteal height. Popliteal height is the distance from the underside of the foot to the underside of the thigh at the knees. Table height was then adjusted to the midpoint between seatpan height and seated eye height. Table and seatpan positioning were modified from Carello et al. (1989) and Choi and Mark (2004). To aid in establishing actual reach limitations for a 1-*df* action (described in the next section), a commercial seatbelt system was modified and secured to the back of the chair. The room was darkened with the exception of light from the computer monitor and white visual images projected onto the table programmed with a gray background surface. The fixation point was projected onto a rectangular box (with a 45 degree angle surface) placed at midline approximately 45cm from most distal target.

Two conditions were conducted: one in which the participants used their effector only (HAND) for reach and the other in which participants used a TOOL (Figure 2).

HAND TOOL

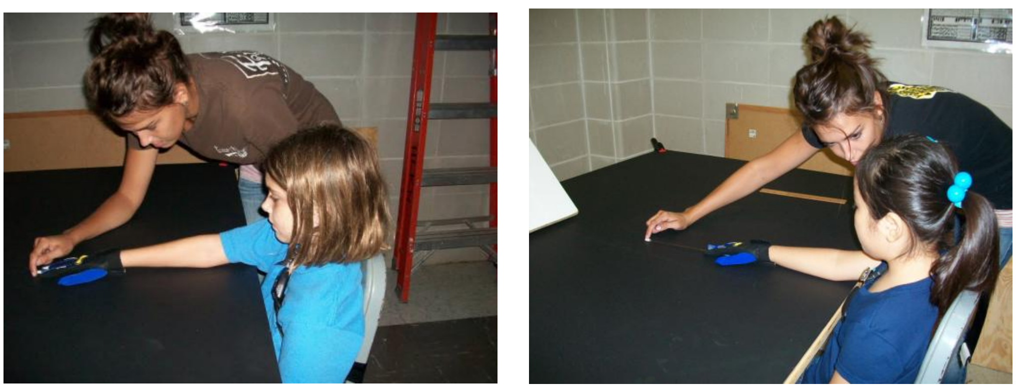

Figure 2. Illustration of HAND and TOOL reach.

For both conditions, participants wore a modified commercial racquet glove that was sized to fit comfortably their right hand; the size range available was XS to XL. The glove was modified as follows. A finger-nail size piece of green luminescent tape was attached to the tip of the middle finger (point of reach determination). In addition, a retractable pen size antenna-type pointer was attached to the under side of the glove with the tip of the pointer even with the tip of the middle finger of the glove. The tip of the pointer also had a piece of luminescent tape attached; both conditions were conducted very dim lighting. For the TOOL condition, the pointer was extended 20cm out from the tip of the middle finger site, whereas for HAND trials, the pointer was retracted (or placed) at actual middle finger tip. Each participant's maximum reach was individually scaled with the hand and tool (as described in Procedure). These measurements provided the base-line comparison for estimates of reach in space.

Procedure

To begin, participants were systematically positioned in the chair and introduced to the task for determining 'actual' maximum reach - full extension of the right limb and middle finger to pull back a penny using a 1-*df* reach (Carello et al., 1989). A 1-*df* reach involved a comfortable effort of the hand forearm, and upper arm acting as a single functional skeletal unit. Based on maximum reach, seven imagery targets (2cm diameter-penny size) were randomly programmed with "4" representing actual reach complemented with three image sites farther and three sites closer touching at the rims. In essence, actual reach was 'scaled' to individual arm lengths, therefore allowing acceptable comparison. For the TOOL condition program, 20cm was added to the HAND maximum reach value. As a reliability check (primarily for violation of 1-*df* constraint), this value was compared to actual maximum reach with the TOOL using the first few participants; values were equivalent.

For the motor imagery trials, using HAND and TOOL, participants were asked to kinesthetically 'feel' themselves executing the movement ("feel your arm extending…"); therefore being more sensitive to the biomechanical constraints of the task (Johnson, Corballis, & Gazzaniga, 2001; Sirigu & Duhamel, 2001; Stevens, 2005). For the HAND condition, the right (focus) hand was placed within a drawn box on the table close to the torso at midline and the non-dominant limb rested on the participant's upper left thigh under the table. Use of the TOOL was similar with the exception that the tool was placed (rested) at a 45° angle parallel to the front edge of the table – right hand place within the box. In this condition, participants were instructed to focus on the illuminated tip of the pointer in order to make the judgments of reachability.

Data collection began with a 5 s verbal "Ready!" signal – that was immediately followed by a central fixation point lasting 3 s, at the end of which the participant heard a tone. The image appeared immediately thereafter and lasted 500 ms. Target presentation was given in random order with participants receiving five trials at each of the seven sites. A second tone then provided the signal for the participant to respond immediately with a "Yes" or "No" in reference to whether the stimulus was 'reachable' or not. A second experimenter served to reinforce instructions regarding imagery technique and refocusing to the central fixation point with each trial.

Prior to actual data collection, each participant was trained in the use of motor imagery, with and without the tool, and allowed practice trials (typically 3-5). During those trials, a few children were excluded (their data) due to immaturity in understanding task instructions or by virtue of answering 'yes' with all trials. We wish to point out that the experimental paradigm using the HAND condition has proven to be effective with children as young as 5 years (Gabbard, Caçola, & Cordova, 2008; Gabbard et al., 2007; Gabbard et al., 2009a).

General Procedure

Each participant performed the HAND and TOOL conditions, which were presented in counterbalanced order. The HAND condition consisted of 42 trials divided into two blocks of 21 trials (participants had a rest break in between blocks) and a 'switch- block' of 7 trials with the TOOL. The TOOL condition involved the same procedure with a switch-block to HAND. Therefore each condition had 42 trials followed by a switch-block of 7 trials of the opposite condition. Between conditions, participants had a larger break; they were instructed get up and move around lab for a few minutes. The intent of the switch-block was to gain insight to the adjustment period associated with extending and retracting space [more detail is provided in the subsequent section].

Individual testing required approximately 45-minutes and was completed within a single session; all testing was conducted in an isolated room.

Treatment of the Data

A previous analysis comparing the two blocks of 21 trials for each condition revealed no differences between the blocks for both HAND and TOOL, therefore data from the two blocks were combined. Total score, representing overall accuracy across targets, was defined as the percentage of correct responses out of the total number of trials of the two blocks (total 42 trials). A correct verbal estimation of reach was when the participant responded 'yes' when actually the target was within reach, or 'no' when the target was out of reach. Targets 1 – 4 were defined as peripersonal (within reach) space, and targets 5-7 as extrapersonal (out of reach) space. These data were analyzed using a 2 (Condition) x 2 (Space) x 4 (Age group) repeated measures analysis of variance (ANOVA) procedure. As appropriate, post hoc analyses using Tukey's tests were performed ($p < .05$). For simplicity of presentation and the fact that there was a difference in the number of trials in peripersonal and extrapersonal space, results are presented of a proportion (% accurate) of total score.

To determine the distribution of error across targets (where did the errors occur?), the number and differences between wrong and right answers for each target, in each condition were calculated using frequency data analyses and chi-square procedures. The reader should keep in mind that there was seven target presentations with '4' representing the participant's actual maximum reach. Incorrect responses at the three targets above (distal to) the actual (5 – 7) indicated an 'overestimation', whereas an incorrect response at any of the lower (proximal) targets (1 – 4) was considered an 'underestimation.' For example, if a participant noted that target 5 was reachable ("yes") when in fact it was not, it was an overestimation. As noted earlier, targets 1-4 were identified as peripersonal (within reach) space, whereas targets 5-7 defined extrapersonal (beyond reach) space.

To gain insight to the adjustment period associated with extending and retracting space, a binary logistic regression with a stepwise variable selection method was fitted to the last block of 7 trials in each series. A logistic regression is a variation of ordinary regression, used when the dependent (response) variable is a dichotomous variable (0 or 1) and the independent (input) variables are continuous, categorical, or both.

We ran one regression for each trial in the switch-block condition, totaling 7 regression procedures. The dependent variable was the score '1' or '0', respectively, representing a correct or incorrect response (estimation accuracy). All independent variables were categorical representing Age, Space, and Condition. For ease of interpretation, results are expressed in terms of odds ratios (OR) and 95% confidence interval (CI). The OR is usually the parameter of interest in a logistic regression, due to its ease of interpretation.

Results

Accuracy

Initial ANOVA and post hoc results indicated that the three children age groups were not significantly different (*ps* > .05), however, each was different from the adult group. Therefore, with the remaining analyses, data for the three child groups were combined and compared to adults. Those results indicated no effect for Condition, $F(1,66) = .28$, $p = .59$, $\eta^2 = .004$; however, there was a distinction for Space, $F(1,66) = 66.45$, $p < .0001$, $\eta^2 = .502$; and Age (children versus adults), $F(1,66) = 41.6$, $p < .0001$, $\eta^2 = .387$; as well as a significant interaction for Age x Space, $F(1,66) = 5.85$, $p < .02$, $\eta^2 = .082$. Figure 3 shows values on the interaction. Simple main effect analyses revealed that both children and adults were significantly more accurate in peripersonal, compared to extrapersonal space. Regarding Space differences, the accuracy of children and adults differed in both peripersonal and extrapersonal space. Values (%) for correct responses were: Children – peripersonal space (89 ± 7) and extrapersonal (62 ± 16); Adults –

peripersonal (94 ± 7) and extrapersonal (80 ± 12). As noted earlier, there was no Condition (TOOL versus HAND) effect.

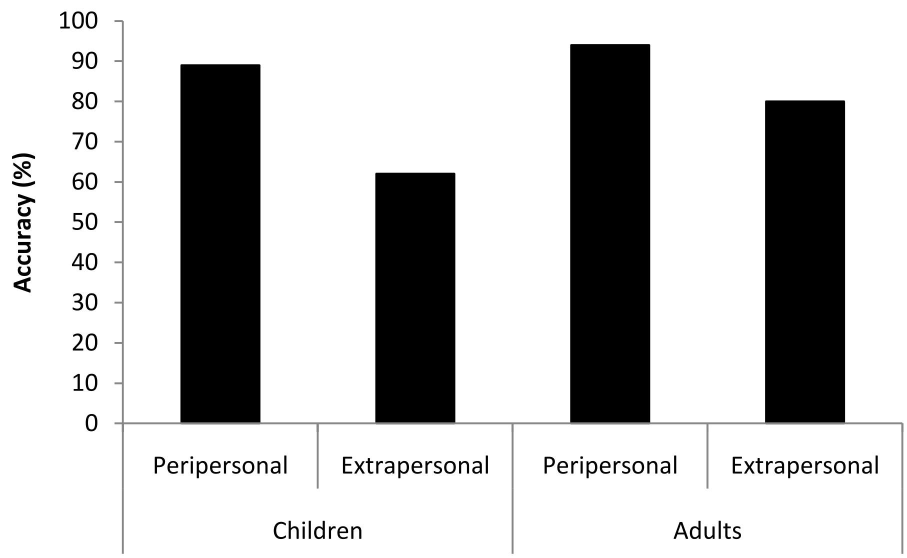

Figure 3. Estimation accuracy by Space and Age in Experiment 1.

Distribution and General Direction of Error

Our attention at that point focused on where the errors occurred. Figure 4 (a, b, c, and d) shows the distribution of error profiles for the two conditions in each age group.

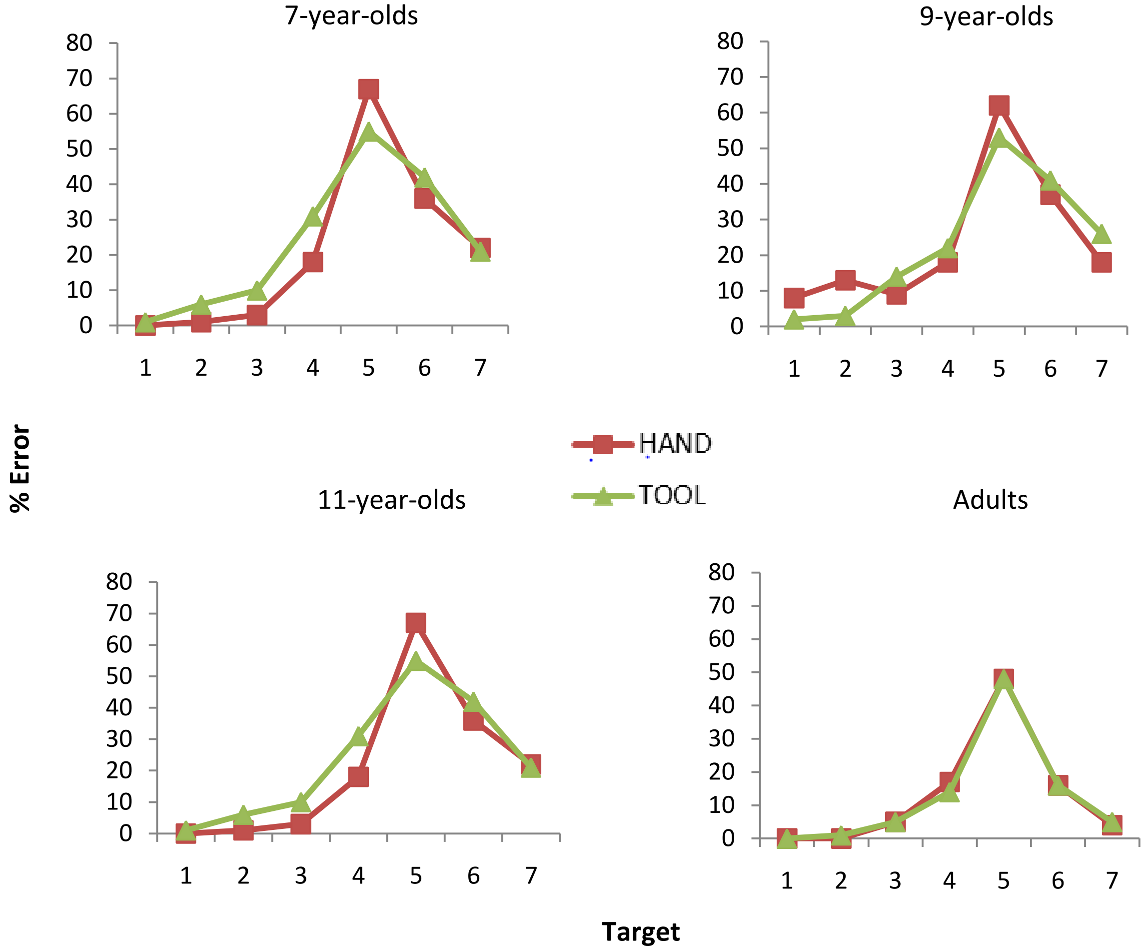

Figure 4. Distribution of error across targets for HAND and TOOL conditions by Age in Experiment 1.

Since there were no differences between conditions for age, we collapsed the data across targets and looked at the differences between children and adults (Figure 5). The highest level of error occurred for both groups at target 5, which represents overestimation (Children: HAND - 61%, TOOL - 57%; Adults: HAND - 48%, TOOL - 48%). Regarding the comparison of children and adults, Figure 6 illustrates and confirms the earlier findings that all groups were more accurate in peripersonal space (representing targets 1-4). Figures 5 and 6 also show that children displayed more errors at all targets with significant distinctions at targets 5-7 (*ps* < .05) compared to adults, which suggests a higher overestimation bias (Children: Target 5, 59%; Target 6, 41%; Target 7, 26%; Adults: Target 5, 48%; Target 6, 16%; Target 7, 4%)

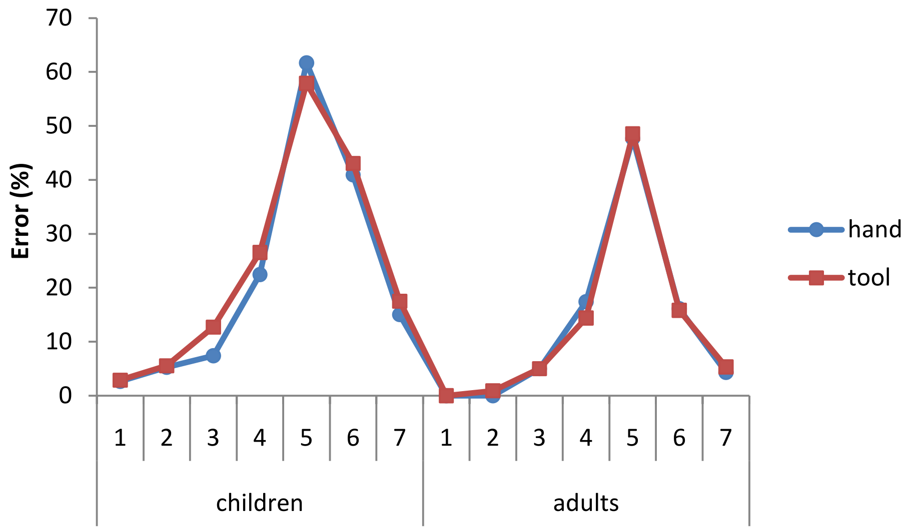

Figure 5. Comparison between children and adults in distribution of error across targets, for HAND and TOOL conditions in Experiment 1.

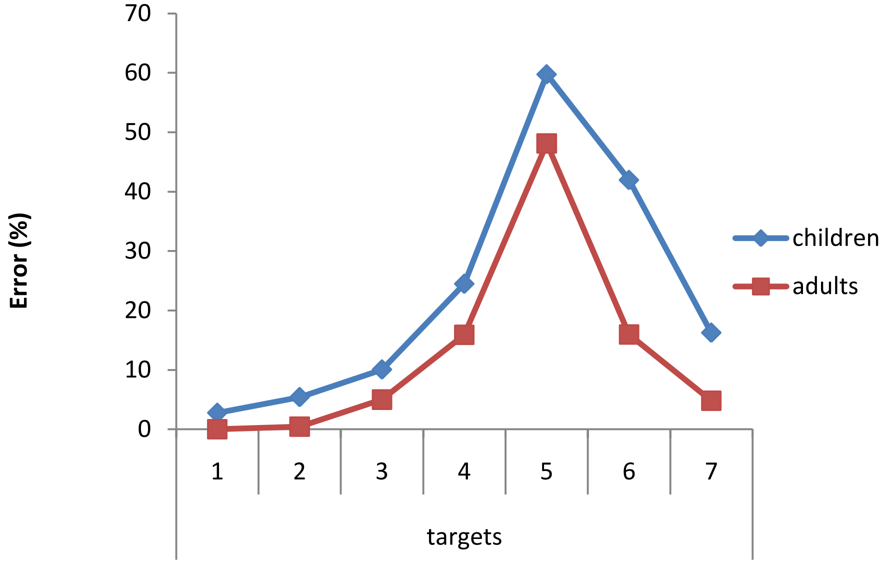

Figure 6. Comparison between children and adults in distribution of error across targets in Experiment 1.

Regression Analyses

Results of the logistic regression analyses are shown in Table 1. We also decided to collapse the child age groups for this analysis.

Table 1. Odds ratios and confidence interval from logistic regression on switch-block conditions in Experiment 1.

Trial	Predictors	Comparison	1 vs. 0 - OR (CI 95%)
1	Space	Peri vs Extra	15 (5.88 – 38.24)***
	Age	Children vs Adults	0.30 (0.11 – 0.75)*
2	Space	Peri vs Extra	33.52 (8.85 – 126.9)***
	Age	Children vs Adults	0.17 (0.05 – 0.53)**
3	Space	Peri vs Extra	13.43 (4.26 – 42.33)***
	Age	Children vs Adults	0.25 (0.08 – 0.73)**
4	Space	Peri vs Extra	9.26 (3.48 – 24.61)***
	Age	Children vs Adults	0.37 (0.15 – 0.88)*
5	Space	Peri vs Extra	2.49 (1.10 – 5.62)*
	Age	Children vs Adults	0.29 (0.12 – 0.72)**
6	Space	Peri vs Extra	13.85 (3.87 –49.52)***
7	Space	Peri vs Extra	7.82 (3.00 – 20.37)***
	Age	Children vs Adults	0.33 (0.12– 0.86)*

* $p < .05$, ** $p < .01$, *** $p < .001$

The findings indicated that children, in general, were less likely to estimate reach correctly in comparison to adults. In addition, all participants were more likely to estimate reach accurately in peripersonal rather than in extrapersonal space; reinforcing previous analyses. For all trials of the switch block except Trial 6, Space and Age were significant. Results indicated that participants were up to 33 times more likely to be accurate in peripersonal than in extrapersonal space (Trial 2); the odds of being accurate for children was only up to 0.33 in comparison to adults (Trial 7).

Discussion

Our intent with Experiment 1 was to investigate the age-related ability to modulate peripersonal and extrapersonal space via hand and tool use. We also aimed to determine the adjustment period associated with extending and retracting spaces. Underscoring our interest was research findings with animals and adult humans suggesting that with tool use neural adaptations occur that remap (what was) far space as near space. Our assumption was that children would show less accuracy than the adult group, and we also expected to find no differences between hand and tool conditions in each age group.

Our data indicated the following: Overall, there was no difference between estimation of reach accuracy between hand and tool use. In addition, the youngest age group performed as well as the two older groups. However, there was a significant Age x Space interaction, which indicated that children were significantly less accurate than adults in general. Also, both groups were significantly more accurate in peripersonal, compared to extrapersonal space. Furthermore, whereas both groups displayed an overestimation bias, the value was greater for the children.

From these results, two observations directed our attention. First, was the striking similarity between hand and tool conditions. This finding supports the idea that altered action capabilities with the tool are accurately represented in the body schema, resulting in the modification of an individual's representation of space (Higuchi, Imanaka, & Patla, 2006). Our findings add to this body of research by establishing that a tool can modulate borders of space in the context of estimation of reach through motor imagery. In addition, these results are supported by previous research that emphasized the ability of the CNS to adapt to altered action capabilities very quickly, for well-learned motor actions (Higuchi et al., 2006).

Secondly, is the resemblance in performance between age groups in the tool condition. Our initial expectations were that participants would have more difficulty with the tool and children, especially the younger group, would show less accuracy than the older groups. From the results found for total accuracy, it would appear that children as young as 6 years of age are capable of re-scaling peripersonal space via tool use in the context of estimation reach. That is, they were capable of extending and retracting the tool in a similar fashion as adults - even though they were less accurate overall, their accuracy level for estimating reach with the tool was not different than their accuracy with the hand. This observation is relevant when we think about the level of experience that 6-year-olds typically have with tools (to eat, play, etc). We can infer that the experience using such tools to achieve goals could speculatively help children perform an estimation reach task as accurately as they would with their hand.

In addition to total accuracy in estimation of reach, we also wanted to gain insight to the adjustment period associated with extending and retracting space; which was examined using the switch-block procedure with trial-by-trial analysis described earlier. In other words, participants would display more error with the tool, especially in the early trial segments. When we looked at the “switch” from one condition to the other after participants had performed 42 trials, we found that accuracy for Condition was not different even for the first of the seven trials. This observation demonstrates that it takes virtually no time for participants to adjust to their normal accuracy range after switching from one condition to the other. As a general observation, these results suggest that spatial extension and retraction for children and adults has a similar, almost immediate, adjustment period; that is, in context of estimation of reach.

This study also supports previous findings regarding the general direction of error and performance differences in peripersonal and extrapersonal space by children. Regarding the direction of the error, studies of reach estimation with children and adults indicate the general tendency to overestimate. That is, individuals tend to perceive that objects are within reach, when actually they are out of grasp (children: Gabbard et al., 2007; Gabbard et al., 2009a; Rochat, 1995; Schwebel & Plumert, 1999; adults: Coello & Iwanow, 2006; Fischer, 2000; Gabbard, Ammar, & Rodrigues, 2005; Robinovitch, 1998; Rochat & Wraga, 1997). Furthermore, there is evidence like that shown in the present study, that this overestimation bias is greater in children compared to adults (Gabbard et al., 2007). That same study, which compared estimates of reach (hand only) between children 5- to 11 years of age and young adults, also found that groups were different in spaces. In addition, adult accuracy was similar for space, whereas the children were less accurate in extrapersonal space. In essence, those findings and the data presented here reveal a body-scaling problem in children when estimating reach in extrapersonal space. Our initial explanation, that also seems relevant in this study, is that the ability to map visual information from extrapersonal space for estimates of reach, emerges sometime between early adolescence (> 11 years) and early adulthood. Given the results reported here, that observation now includes reach estimation in extrapersonal space via tool use.

In conclusion, although children had more difficulty with estimating reach with hand and tool compared to adults, their adjustment to tool use was similar to adults. Furthermore, both groups adjusted to the switch from one condition to the other immediately, rather than gradually across several trials. However, the question of whether modulation of space is dependent upon length the tool remains unanswered. Would participants display the same behavior when using a tool twice the length of the tool used in Experiment 1? Experiment 2 addressed this question.

CHAPTER III

EXPERIMENT 2

In Experiment 1, results demonstrated that children as young as 6 years of age are capable of re-scaling peripersonal space via tool use in the context of reach estimation. In addition to the surprising fact that the youngest age group performed as well as the two older children age groups, there was no difference between estimation of reach accuracy between hand and tool use for any age. In this experiment, the tool was 20cm long, approximately the size of an adult's forearm. Arguably, the ease of re-scaling and transition between hand and tool conditions could have happened due to the relatively small length of the tool. In Experiment 2, we examined if re-scaling of peripersonal and extrapersonal space and the adjustment period could be influenced by tool length. To address this issue, we doubled the size of the tool (40cm long) in Experiment 2. Pilot testing indicated that this size is anatomically functional for the youngest participants (6 years of age).

Therefore, the aim of Experiment 2 was twofold: (a) to investigate whether a tool of 40cm length influences the age-related ability to modulate peripersonal and extrapersonal space, and (b) to determine the adjustment period associated with extending and retracting space with a longer tool. In order to explore these aims, a tool of 40cm was used for comparison of estimation of reach responses between effector (hand) and tool.

According to Medina & Coslett (2010), evidence from patients has shown that primary somatosensory representations are plastic, dynamically changing in response to central or peripheral alterations, as well as experience. One could speculate, based on Medina & Coslett's consideration, that the ease in which young children were able to modulate peri- and extrapersonal space is related to many previous experiences using "tools" in daily-living skills (e.g.; silverware, toys, remote controls, etc).

However, it is yet unknown whether longer tools influence modulation of space and children's adaptation to new action capabilities (afforded by the tool). There is a reasonable assumption that children will have more difficulty with a longer tool, based on the findings that children have a body-scaling problem in estimating reach in extrapersonal space (e.g., Gabbard et al., 2007, *Developmental Neuropsychology*). Here, we intended to answer the following question: Are the same behaviors showed when using a tool that is double the length of the tool used in Experiment 1?

Method

Participants

Experiment 2 involved 55 participants representing four age groups: 6 -7 years (*n* = 14), 8-9 years (*n* = 11), 10-12 years (*n* = 11) and a group of adults, 19-23 years (*n* = 19). The mean ages were 7.29, 8.91, 10.55, and 20.58 years, respectively. All participants were screened using a questionnaire (filled out by the parent in the children groups) to ensure normal vision and that none have a history of past or present sensorimotor impairment. For the purposes of this study, only participants identified as strong right-handers via manual performance rather than questionnaire were selected. That is, those for whom all items scored in that lateral direction using the Lateral Preference Inventory (Coren, 1993) were included in the investigation.

The experimental protocol and consent form were approved by the Texas A&M Institutional Review Board (IRB) for the ethical treatment of human subjects. The participants were informed of the experimental procedures and voluntarily signed a consent form before participating in this study (children provided verbal consent after parents signed the consent form).

Apparatus

The apparatus for this experiment was identical to the apparatus in Experiment 1 with the exception of the length of the tool (40cm instead of 20cm).

Procedure

See details regarding the procedures on Experiment 1.

General Procedure

Experiment 2 followed the same procedure as Experiment 1, however; we made one small adjustment. In Experiment 1, each condition (HAND and TOOL) consisted of 42 trials divided into two blocks of 21 trials (participants had a rest break in between blocks) and a ‘switch- block’ of 7 trials with the TOOL; and the TOOL condition involved the same procedure with a switch-block to HAND. Since no differences between the first block of 21 trials and the second block of 21 trials were found in both conditions in Experiment 1, we decided that in Experiment 2, for the sake of time and attention span of the children, to have only one block of 21 trials in each condition, followed by a “switch-block” of 7 trials of the opposite condition.

Treatment of Data

As with the data analysis of Experiment 1, descriptive statistics, analysis of variance (ANOVA) and logistic regression procedures were employed. All the variables were determined the same way as in Experiment 1.

Results

Accuracy

ANOVA results indicated no effect for Condition, $F(1, 51) = .738$, $p > .05$, $\eta^2 = .088$, however; there was an effect for Space, $F(1, 51) = .4.89$, $p < .04$, $\eta^2 = .034$, revealing that participants were more accurate in Extrapersonal (84 ± 18) compared to Peripersonal (75 ± 19); and for Age, $F(3,51) = 9.26$, $p = .001$, $\eta^2 = .353$. Post-hoc analysis indicated that the adult age group (88 ± 9) differed from both the 7-year-olds (71 ± 12) and 9-year-olds (75 ± 9). The 11-year-old group (82 ± 7) was not different than any other group. Even though none of the interactions were significant, Figure 7 shows the estimation of accuracy for Space and Age values.

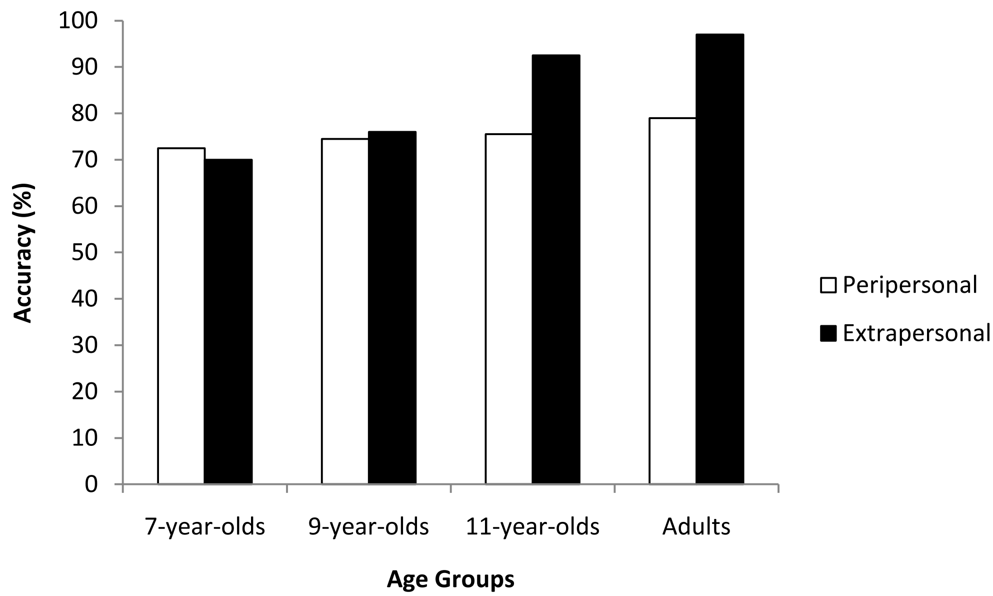

Figure 7. Estimation accuracy by Space and Age in Experiment 2.

Distribution and General Direction of Error

Our attention at this point focused on where the errors occurred. Figure 8 (a, b, c, and d) show the distribution of error profiles for the two conditions in each age group.

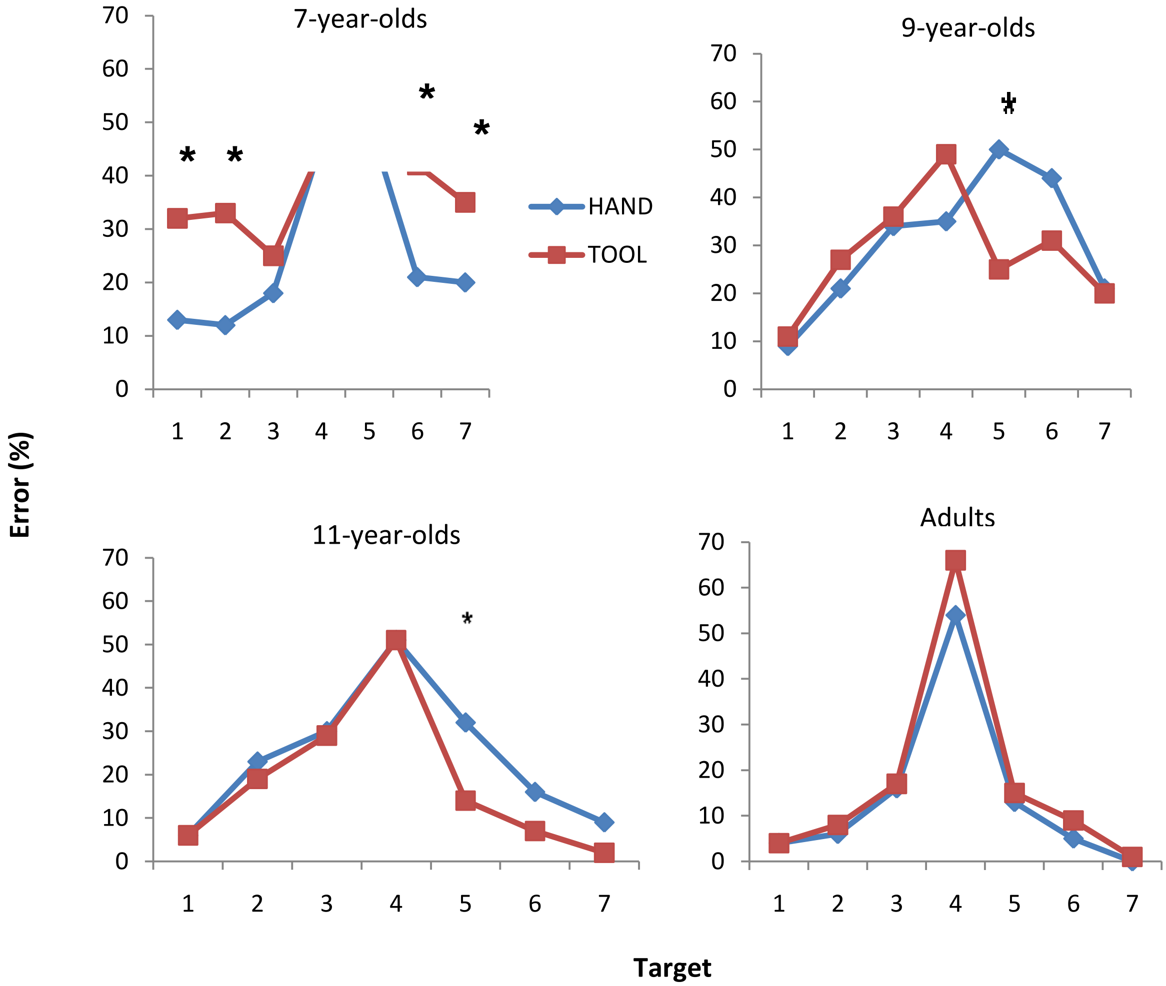

Figure 8. Distribution of error across targets for HAND and TOOL conditions by Age in Experiment 2.

While there were no differences between conditions in each target for the adult age group, we found some target differences ($\chi^2_{(1)}$ with *ps* < .001 unless otherwise noted) in the children age groups. For the 7-year-olds, the differences between hand and tool were in targets 1 (HAND: 13%, TOOL: 32%), 2 (HAND: 12%, TOOL: 33%), 6 (HAND: 21%, TOOL: 42%) and 7 (HAND: 20%, TOOL: 35%). For the 9- and 11-year-olds, the difference was in target 5 (9-year-olds: HAND: 50%, TOOL: 25%, 11-year-olds: HAND: 32%, TOOL: 14%), and both age groups were more accurate with the tool.

Overall, most errors occurred around targets 4 and 5, as depicted by the comparison of children and adults (Figure 9).

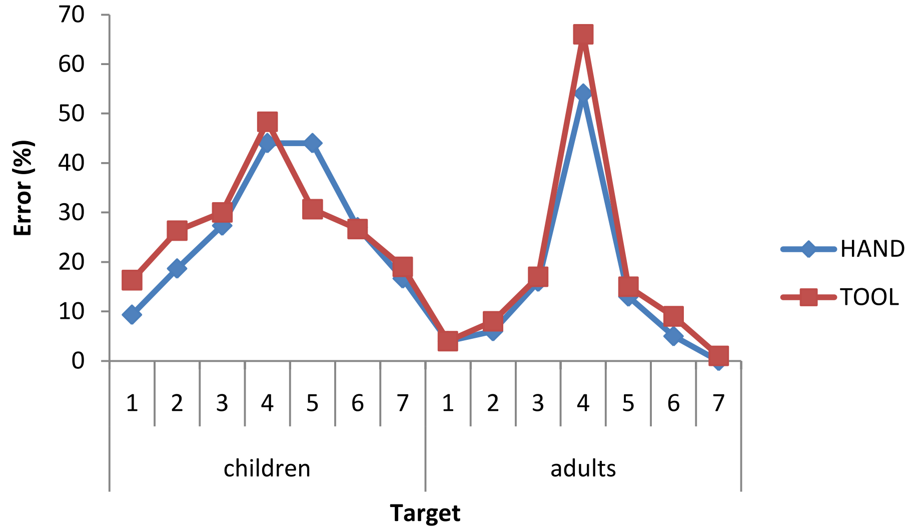

Figure 9. Comparison between children and adults in distribution of error for HAND and TOOL conditions.

Regression Analyses

Results of the logistic regression analyses showed that only Age was significant, and only in Trial 1. Space and Condition were not significant. Table 2 shows the values for each trial:

Table 2. Odds ratios and confidence interval from logistic regression on switch-block conditions in Experiment 2.

Trial	Predictors	Comparison	1 vs. 0 - OR (CI 95%)
		7- year-olds vs Adults	0.32 (0.10 – 0.99)*
1	Age	9- year-olds vs Adults	0.21 (0.06 – 0.68)*
		11- year-olds vs Adults	0.72 (0.19 – 2.61)*

* p <.05, ** p < .01, *** p < .001

The findings indicated that children, in general, were slightly less likely to estimate reach correctly in comparison to adults. Younger children (7- and 9-years of age) were similarly less likely to be accurate than adults, while the 11-year-old age group was the least accurate of all. Differences in space reinforced previous analyses, showing that accuracy was mainly dependent upon space, regardless of condition.

Comparative Analysis of Experiments 1 and 2

In order to compare the data from Experiment 1 and Experiment 2, additional statistical procedures were employed. First, an ANOVA Procedure (similar to the one run in each experiment) was conducted, with the addition of the factor "Experiment [1/2]". There were no significant differences for any of the factors (Experiment, Condition, Age Group, Space). A similar analysis run separately for each age group, revealed the same results found in each Experiment.

For distribution of error, a distinct trend for each experiment was found. A comparison by experiments in each group is shown on Figure 10:

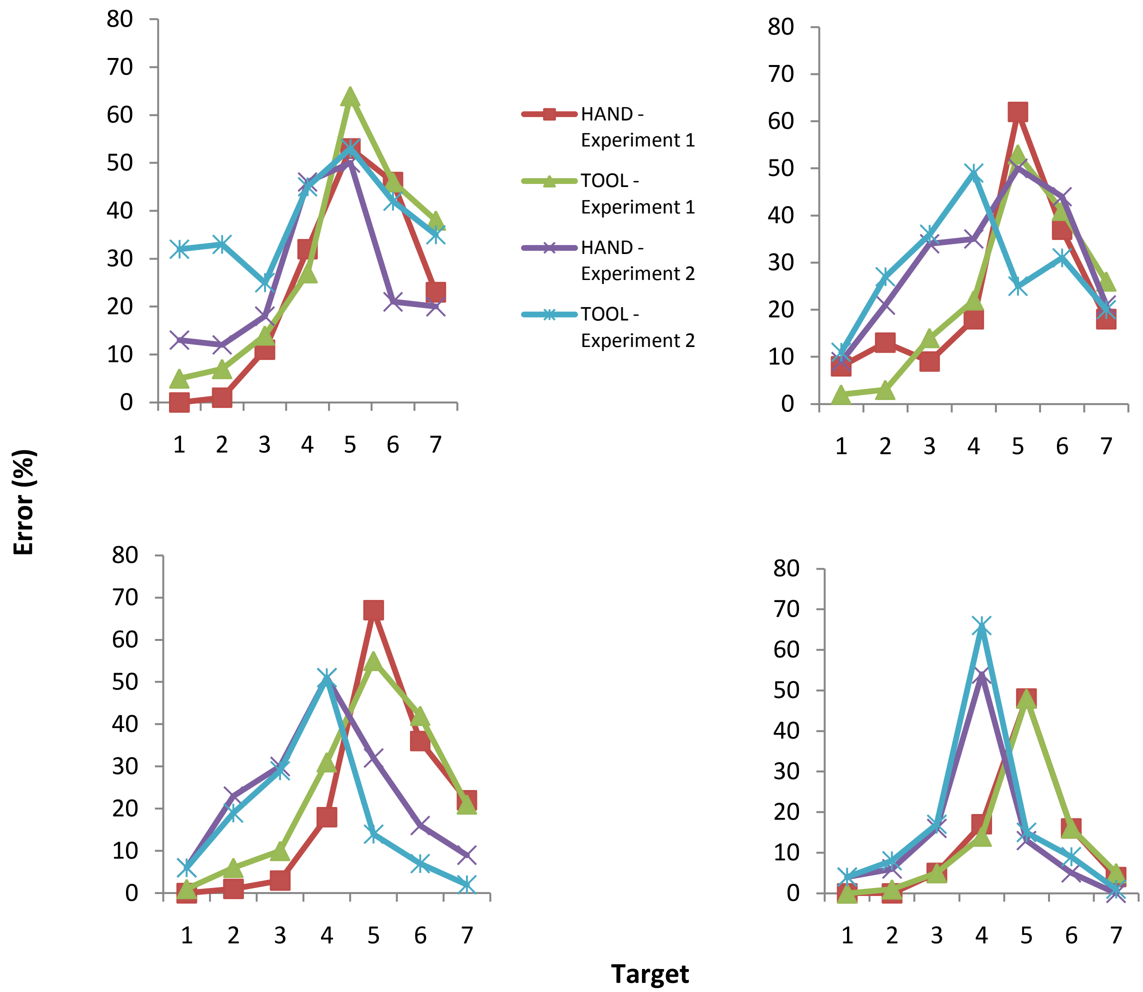

Figure 10. Comparison between experiments in distribution of error across targets by Age.

The comparison of experiments by age group revealed the following differences: For 7-year-olds, the differences were in targets 1, 2, and 6 in the HAND condition, and in targets 1, 2, and 4 in the TOOL condition. Nine-year-olds were different in targets 3 and 4 on HAND condition, and targets 1, 2, 3, 4, and 5 in TOOL. For 11-year-olds, all targets were different in the HAND condition, and all targets in the TOOL condition except 1. Adults were different in targets 2, 3, 4, 5, and 6 in HAND, and targets 2, 3, 4, and 5 in TOOL. Table 3 shows the percentage of error in each target and condition by experiment and age group.

Table 3. Comparison of error (%) by target in Experiments 1 and 2.

Age Group	Target	Hand Exp. 1	Hand Exp. 2	Difference	Tool Exp. 1	Tool Exp. 2	Difference
7-year-olds	1	0	13	*	5	32	*
	2	1	12	*	7	33	*
	3	11	18		14	25	
	4	32	46		27	45	*
	5	53	50		64	53	
	6	46	21	*	46	42	
	7	23	20		38	35	
9-year-olds	1	8	9		2	11	*
	2	13	21		3	27	*
	3	9	34	*	14	36	*
	4	18	35	*	22	49	*
	5	62	50		53	25	*
	6	37	44		41	31	
	7	18	21		26	20	
11-year-olds	1	0	6	*	1	6	
	2	1	23	*	6	19	*
	3	3	30	*	10	29	*
	4	18	51	*	31	51	*
	5	67	32	*	55	14	*
	6	36	16	*	42	7	*
	7	22	9	*	21	2	*

Table 3. Continued.

Age Group	Target	Hand Exp. 1	Hand Exp. 2	Difference	Tool Exp. 1	Tool Exp. 2	Difference
	1	0	4		0	4	
	2	0	6	*	1	8	*
	3	5	16	*	5	17	*
Adults	4	17	54	*	14	66	*
	5	48	13	*	48	15	*
	6	16	5	*	16	9	
	7	4	0		5	1	

The discussion of the comparison between Experiments is provided in the next Chapter IV.

Discussion

Our intent with Experiment 2 was to investigate whether a tool of 40cm influenced the age-related ability to modulate peripersonal and extrapersonal space via hand and tool use, and also to determine the adjustment period associated with extending and retracting space with a longer tool. Our assumption was that children would again, as in Experiment 1, show less accuracy than the adult group. We also expected to find differences in hand and tool conditions because of the longer length of the tool.

Our data indicated the following: Overall, there was no accuracy difference in hand and tool conditions, but there was a difference in Space and Age. In addition, a post-hoc analysis showed that 7 and 9-year-olds performed at the same level, but differed from adults. Interestingly, the 11-year-olds did not differ from any other age group. The lack of difference between conditions and the difference in age were the most important findings with accuracy.

Initially, we expected a difference between conditions since the length of the tool was twice the size of the length used in Experiment 1. Interestingly, our results did not confirm our expectations. This finding confirms the notion that altered action capabilities with the tool are accurately represented in the body schema (Higuchi et al., 2006), and adds to the current body of research by specifying that length of the tool does not influence re-scaling of peripersonal space in the body schema. We can speculate two reasons for that result: 1) the length of the tool does not influence modulation of space because a tool of any length is able to serve its function of modifying (expanding) the body schema as long as it is attached to the body and have a specific purpose (e.g., reaching for a target), and 2) perhaps experience is a factor on how the body represents and re-scales space by a tool. It is very likely that every 6-year-old had at least some experience with a toy or sport equipment that was 40cm or longer – which may have facilitated their re-scaling of space with this length of tool.

However, when looking at accuracy in Space only, interesting findings emerged. Overall, participants tended to be more accurate in extrapersonal space. This finding is somewhat surprising because in previous studies, we found that participants were more accurate in peripersonal space and tend to overestimate their reaching abilities (Gabbard et al., 2005; 2007; 2009a). In the present experiment, participants underestimated their reaching abilities. Because there were no differences in Hand and Tool conditions, it is unlikely that the underestimation only happened when estimating reach with the tool, but we speculate that being presented with a longer tool influenced confidence levels of participants (especially 11-year-olds and adults), therefore shifting their general direction of error.

The distribution of error specific to the seven targets used in this study gives us specific trends on space by age group. When looking at 7-year-olds specifically, differences were in targets 1, 2, 6 and 7, with the error always higher in the tool condition. This finding shows that for this group, the critical boundary (targets 4 and 5) is the area of higher mistakes (citations), regardless of the condition. However, for all other targets, the percentage of error was always higher in the tool Condition.

Nine (9) and 11-year-olds differed only in target 5, and interestingly, the error was higher in the hand condition. This finding shows what happens with the critical boundary when using a tool. Overall, studies have found that participants tend to make more mistakes in target 5 (Gabbard et al., 2007), but with the tool, the critical boundary effect is somehow minimized, and less errors occur. In adults, the error distribution is similar, regardless of conditions, but more errors are made in target 4 (participants' actual reach), reinforcing the underestimation trend found in the previous analysis.

The second intent of this experiment was to look at the adjustment period associated with extending or retracting a tool. The analysis by trial showed that only in Trial 1 age groups were different; all children groups were slightly less likely to be accurate then adults (OR: .32 (7), .21 (9), and .72 (11)). There was no condition difference in any of the trials, demonstrating that with a tool of 40cm, the adjustment period is immediate rather than gradual.

In conclusion, a tool of 40cm did not reveal accuracy differences in hand and tool conditions. We found a specific age difference – 7- and 9-year-olds were less accurate than adults, while 11-year-olds were not different than any other age group. We also conclude that there seems to be a shift related to errors in space with the 40cm tool, where participants exhibited underestimation. Condition also, does not seem to influence the adjustment period associated with extending or retracting a tool. A discussion comparing Experiments 1 and 2 will follow in Chapter IV.

CHAPTER IV

DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

General Discussion

The primary goal of this study was to gain insight into the developmental nature of spatial perception and representation in reference to children's modulation of peri- and extrapersonal space. More specifically, we examined the developmental nature of spatial perception and representation in regard to the ability to use a) hand and b) tool.

This study asked the following research questions: *Is there an age-related ability in modulation of peri- and extrapersonal space? Is there an adjustment period associated with extending and retracting space via tool use? If so, how long is this period? Is the ability to modulate space and the adjustment period related to the length of the tool used?*

Two experiments were designed to address the aims of this study. Experiment 1 examined the age-related ability to modulate peripersonal and extrapersonal space via hand and tool use. In addition to performance outcome over trials, we determined the adjustment period associated with extending and retracting space via hand and with a tool of 20cm length. Our assumption was that children would show less accuracy than the adult group. We also expected to find no differences between hand and tool conditions in each age group. This prediction was based on evidence suggesting that tool use result in an expansion of the body schema and peripersonal space.

With Experiment 2, we investigated whether a tool of 40cm influenced the age-related ability to modulate peripersonal and extrapersonal space, and we also aimed to determine the adjustment period associated with extending and retracting space with a longer tool. We expected that children would show more difficulty with a longer tool, based on the findings that children have a body-scaling problem in estimating reach in extrapersonal space (e.g., Gabbard et al., 2007). The two experiments used a paradigm for comparison of estimation of reach responses between hand and tool.

In regard to our initial question: *Is there an age-related ability in modulation of peri- and extrapersonal space?* There were no differences in modulation of space by any of the age groups used in this study. Overall, children were always less accurate than adults, but the average accuracy for each age group remained similar, whether participants were using their hand or a tool. In addition, the age-related ability in modulation of space was not related to the length of the tool. Even though we expected to find accuracy differences between hand and the 40cm tool in the younger age groups, our results did not support this expectation. Again, we found that overall, children were less accurate than adults, but never less accurate with the tool when compared to the hand.

While in Experiment 1 all children were similarly less accurate than adults, age differences were more subtle in Experiment 2. Overall, 7- and 9-year-olds performed at the same level, but were less accurate than 11- year-olds and adults. This difference suggests a developmental trend for accuracy in estimation of reach ability, divided in childhood, adolescence, and adult years, likely to be associated with changes in body size (relative sizes and shapes of the limb, body, and head) and postural re-mapping caused by those changes.

This developmental trend certainly follows the development of action representation abilities, since our participants were asked and trained to use motor imagery when estimating reach, with both the hand and the tool. Research suggests that children as young as 5 years of age have the ability to imagine movements (Funk et al., 2005), and motor imagery ability appears to be still emerging at 7 years of age (Molina, Tijus, & Jouen, 2008; Frick et al., 2009). In addition, it is likely that developmental changes specific to generating accurate motor images are refined during adolescence (Choudhury et al., 2007), a notion that is closely associated to our accuracy findings.

In summary, the ability to specifically modulate spaces via tool use is not age-related – children can extend their peripersonal space with tools of 20 and 40cm and estimate reach as accurately as they were with their hand. Obviously, based on our results, their average accuracy with the hand and tool is lower than in adults. This finding suggests, speculatively, that the differences in accuracy are related only to the development of action representation through motor imagery, and not differences in the ability to modulate peri- and extrapersonal space.

With regard to question 2: *Is there an adjustment period associated with extending and retracting space via tool use? If so, how long is this period?* The best way to look at the adjustment period was by performing analyses by trial. With both Experiments 1 and 2, we found that the adjustment period associated with extending and retracting space was very short (immediate), in other words, participants are as accurate with their hand as they are with either tool length right on the first trial of the switch-block. This result was not surprising according to Higuchi et al. (2004), who argue that having the “tool” attached to their hand at the time of the estimates possibly allowed subjects to gather information about their action capabilities, contributing to their quick adaptation to the altered condition. Our findings are consistent with research suggesting that “individuals can adapt very quickly to new action capabilities when they are using a tool, as if the tool were incorporated into the body” (Berti & Frassinetti, 2000; Farnè & Làdavas, 2000; Maravita et al., 2002; Mark, 1987; Turvey, 1996).

In regard to question 3: *Is the ability to modulate space and the adjustment period related to the length of the tool used?* Overall, a comparison of the results found in Experiments 1 and 2 indicated that the overall ability to modulate space and the adjustment period for extending and retracting spaces is not related to the length of the tool. First, participants were as accurate with their hand as they were with the tool in both experiments. None of the age groups were different when comparing their hand and tool accuracy results, in both experiments, suggesting that the length of the tool does not influence modulation of space. Because there were no overall differences in modulation of space even with our version of a “longer” tool, we speculate that this length of tool could be described as somehow short when compared to real-world experiences, meaning that most practical experiences with tools, even for a 6-year-old child, are easily around 40cm.

The similarity of accuracy for both tool lengths adds to the body of behavioral evidence showing that the brain codes space in terms of reachability (Iriki et al., 1996), and that the adjustment period is abrupt and quick, for well-learned motor actions (Higuchi et al., 2006; Gamberini et al., 2008). Basically, Experiments 1 and 2 confirmed certain characteristics of spatial modulation and confirmed the already expected age-related trend in accuracy.

However, when taking a close look at what space the errors were, we found an interesting trend - participants were more accurate in extrapersonal space, especially 11-year-olds and adults, which shifts the general distribution of error from Experiment 1 to Experiment 2. In Experiment 1, participants overestimated more, whereas in Experiment 2, they tended to underestimate their reaching abilities. We speculate that the longer tool could have influenced confidence levels of participants, because of its length, reflecting in more errors in peripersonal space, regardless of condition.

The view of where the errors were based on the seven targets used in the experiments brings more clear differences between the two tool lengths and age. In Experiment 2, our youngest age group made more mistakes with the tool in the extremes (targets that were too close or too far). A comparison of the tool lengths revealed that with the 40cm tool, there were significant errors in targets 1 and 2 (peripersonal space), but not with the 20cm tool. On the other hand, in extrapersonal space, targets 6 and 7, the errors with the two different lengths of tool were similar. The 9-year-old age group was also less accurate in peripersonal space in Experiment 2. In extrapersonal space, only with the longer tool were children more accurate, surprisingly. Somehow the mistakes in Experiment 2 were shifted to the targets in peripersonal space, in comparison with Experiment 1. Those findings reinforce the space differences previously commented on, and the notion that perhaps a longer tool may influence confidence of individuals, leading to underestimation rather than overestimation.

The space differences and distribution of error analysis related to targets give a clear perspective of differences between lengths of the tool. The shift of errors from extrapersonal space with the "shorter" tool to peripersonal space with the "longer" tool clearly demonstrates that the ability to modulate space is related to the length of the tool. For example, in this case, a longer tool made clear to the participant that an object was not reachable in extrapersonal space, therefore the higher levels of accuracy. In contrast, it made peripersonal space more difficult to be estimated.

Taken together, results from Experiment 1 and 2 combine to show the complexity of sensorimotor behavior that tool use represents (Holmes et al., 2004). In addition to establish that modulation of space is not age-related, the combination of experiments shows that the developmental trend and the characteristics of space perception, recognition, and modulation are not dependent upon changes in tool length.

Conclusions

Based on the obtained results and limitations of this investigation, the following conclusions seem warranted:

1. *Is there an age-related ability in modulation of peri- and extrapersonal space?* Our results showed that there is not an age-related ability in modulation of peri- and extrapersonal space, regardless of the length of the tool. Overall, with both the 20 and 40cm tool, children and adults can extend and retract spaces (using hand and a tool) in the same fashion, although children are significantly less accurate than adults. This difference establishes a developmental trend in estimation of reach accuracy divided in childhood, adolescence, and adult years, suggesting that the ability to accurately

modulate space is most likely related to developmental differences in action representation and use of motor imagery.

2. *Is there an adjustment period associated with extending and retracting space via tool use? If so, how long is this period?* In the context of our estimation of reach task, which involves motor imagery, we found that the adjustment period or transition from hand to tool or tool to hand is abrupt/quick, rather than gradual. In other words, extending and retracting space via tool use is an example of the ability of the CNS to adapt to altered action capabilities very quickly. Our findings also suggest that the adjustment period is not dependent upon the length of the tool.

3. *Is the ability to modulate space and the adjustment period related to the length of the tool used?* Our data suggests that the ability to modulate space is not related to the length of the tool. Accuracy for both tool lengths, when compared to the performance when using hand, was similar. Children also tended to be less accurate than adults overall, regardless of the length of the tool. These results suggest that experience might play a role in modulation of space – we are confident that all of our youngest participants had some sort of experience with toys or home materials that were at least 40cm long – therefore, accuracy in estimating reach with a tool of 40cm was not different than estimating reach their hand. In regards to the adjustment period, both tool lengths confirmed that the adjustment period is quick.

However, we suggestion that tool length play a role in modulation of space by shifting error trends – participants overestimated more with the 20cm tool but underestimated with the 40cm tool. In conclusion, it seems that length of the tool influence confidence level for estimates of reach ability.

Overall, our attempts to explore the age-related ability and the adjustment period with two different lengths of a tool revealed that there is not an age-related ability in modulation of peri- and extrapersonal space. We were also able to conclude, speculatively, that the adjustment period in extending or retracting spaces is quick, at least in the context of an estimation of reach task. Finally, our data suggested that different tool lengths affect confidence levels, shifting error trends for modulation of space.

Limitations and Recommendations

Although the present study addressed significant objectives, our conclusions were limited on some aspects. The first one is the limitation related to the context of the task, estimation of reach via motor imagery instead of using actual and kinematic parameters. Secondly, our paradigm, due to its behavioral nature, could not depict the areas of the brain involved in each experiment. In regard to the extension of this work, future studies should further examine the issue of spatial extension in children, with different tool lengths, considering tasks that require different perceptual abilities, and also exploring further the critical boundaries in space.

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VITA

Name: Priscila Martins Caçola

Address: TAMU 4232
College Station, TX 77843-4243

Email Address: priscilacacola@hlkn.tamu.edu

Education: B. S., Physical Education, Federal University of Parana, 2004
M. S., Motor Behavior, Federal University of Parana, 2006
Ph.D., Kinesiology, Texas A&M University, 2011